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Experimental Investigation of Various Solid Particle Materials on the Steady State Gas-Solid Fluidized Bed System

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ABSTRACT

The present study provides a comprehensive experimental work about fluidized bed gas-solid system characteristics by using different solid particles. Naphthalene, silica gel and sand (197 μm diameter) are utilized as a solid particles while air is used for fluidization. An experimental rig is build to test the various solid particles and to establish a good description of flow and heat transfer patterns for the fluidized bed gas-solid system. Based on the experimental tests, it is found that the solid particle type has a significant influence on the gas-solid flow dynamics. The experimental tests are performed for various fluidized bed velocities (0.8 , 1.2 and 1.6 m/sec) and when the heat fluxes are varied as 80 , 120 and 160 W respectively. Experimental measurements are carried out under steady state situation. Depending on the experimental results , it can be concluded that sand solid particles are better than silica gel and naphthalene solid particles for heat transfer enhancement. Also, it can found for naphthalene , silica gel and sand solid particles that as the fluidized bed velocity and heat flux increase the temperature distribution along the fluidization column increases. Moreover, an empirical equation based on the experimental measurements which linking between Nusselt number (Nu) , Froude number (Fr) and Reynolds number (Re) is suggested. Comparisons with previously published works on gas-solid fluidized bed system are performed and good agreements between the results are observed.

KEYWORDS: Heat transfer , Fluidized bed , Gas-solid flow , Experimental work , Solid particle

Nomenclature:		
Symbol	**Description**	**Unit**
Fr	Froude number	
Nu	Nusselt number	
Re	Reynolds number	
T	Temperature	°C
z	Location at fluidization column height	m
Subscripts		
p	Particle	
Abbreviations		
CFB	Circulating Fluidized Bed	
CFD	Computational Fluid Dynamics	
FCC	Fluid Catalytic Cracking	
ID	Internal Diameter	
LDV	Laser Doppler Velocity meter	

1. INTRODUCTION

Gas-solid or liquid fluidization is defined as an operation in which bed of solid particles are suspended in gas and liquid, due to the net drag force of the gas and/or liquid flowing opposite to the net gravitational force or the buoyancy forces on the particles. This operation is widely used in industrial processes, (e.g.

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Fischer-Tropsch synthesis, acrylonitrile production, fluid catalytic cracking (FCC) , heat exchangers, chemical reactors, dryers, silicon chloridization and particle drying) due to its large gas-particle contact area, good mixing, high heat and mass transfer rates and relatively low axial mixing of the gas. Despite of its practical importance, fluidization has received much less attention than other flow regimes and many important aspects of hydrodynamics of fluidized systems are still poorly understood, probably due to the significant complex dynamic flow behavior **[1]**. Gas-solid fluidized systems are characterized by temperature uniformity and high heat transfer coefficients, due to the intense mixture of the solid material by the presence of gas bubbles. Numerous experimental and numerical research works **[2-6]**, have been published on fluidized bed under various conditions. **Manocchella et al. [7]** operated a cold model of a circulating fluidized bed with a 0.030m-ID, 2.77 m- high riser in a wide range of operating conditions. Several solids were tested, from 57 μm to 1830 μm in size and from 1100 kg/m^3 to 2540 kg/m^3 in density. Pressure fluctuations were measured at several points along the riser, and time series were processed to evaluate chaotic invariants. Axial profiles of average values of pressure and voidage were also evaluated. Three regions were identified in the voidage range investigated : particles-controlled region, clusters-controlled region and bottom-bed-controlled region. **Ciesielczyk et al. [8]** proposed a kinetics equation for both characteristic drying periods based on experimental results on kinetics of silica gel polytetrafluoroethylene, sand and ammonium sulphate drying in fluidized bed and a correlation equation for the mean gas solid heat transfer coefficient in the constant-drayng-rate period. The suitability of introducing the shape factor of the solid particle into the kinetic equation was also studied. **Hidaka et al. [9]** investigated flow behavior of liquid and multi-component mixtures of solid particles in fluidizing columns with an external conduit for a self-circulating operation by an air lift effect. Experimental and analytical results were presented for circulating rates of liquid and particles and for axial changes in holdups of gas and solid in the column. It was found that a one-dimensional sedimentation-dispersion model and mechanical energy balance equation were successfully applied to predict the axial change in gas and solid holdups as well as the circulating rates of liquid and solid particles in the columns. **Zhang et al. [10]** measured local transient solid fraction and particle velocity signals in a 0.418-m I.D. and 18-m high large-scale circulating fluidized bed (CFB) by a dual-optical fiber density probe and a Laser Doppler Velocimeter (LDV) system. The results indicated that two-phase solid flow structure exists in the riser and a significant difference were found in the solid flow structure and the particle cluster mechanism between the gravity-assisted gas–solid flow in the downer and the against-gravity flow in the riser. **Heinrich et al. [11]** developed a model by taking into consideration the heat and mass transfer processes in liquid-sprayed fluidized beds which were used for granulation, coating and agglomeration. Conclusions were drawn on the relevance of particle dispersion, spraying and drying to temperature and concentrations distributions. They concluded that their model could be coupled with a population balance model to describe the particle size distribution and the seeds formation for continuous external fluidized bed spray granulation. **Yusuf et al. [12]** studied heat transfer from a heated wall in a gas fluidized bed using the Eulerian-Eulerian approach. A two dimensional simulation of a bubbling bed at ambient conditions with a heated wall at 333 K was carried using FLOTRACS-MP-3D code. The effects of bubble rise on the heat transfer coefficient were investigated. Comparisons of numerical predictions against experimental data for the effect of gas velocity and particle size on wall to bed heat transfer coefficient were also presented. **Pécora** and **Parise [13]** presented an experimental study of a continuous gas-solid fluidized bed with an immersed horizontal tube. Silica sand (254μm diameter) was used as solid particles and air was used for fluidization in a 900mm long and 150mm wide heat exchanger. Measurements were made under steady state conditions for a solid particle mass flow rate from 14 to 95 kg/h and a number of baffles from 0 to 8. Results showed that the heat transfer coefficient increased with the solid particle mass flow rate and with the number of baffles, suggesting that these were important factors to be considered in the design of such equipment. An empirical correlation for the heat transfer coefficient was proposed as a function of solid particle and gas mass flow rate, number of baffles and gas velocity. **Hussain et al. [14]** performed a numerical study to understand the influence of various riser exit geometries on the hydrodynamics of gas-solid flow in the riser of a circulating fluidized bed (CFB). An Eulerian continuum formulation was applied to both phases. A gas-particle computational fluid dynamics model of flow had been investigated using CFD software FLUENT. The computational model was used to simulate the flow behaviour in the riser and exit geometries under same operating conditions. It was found that the k-ε turbulence model predicted good mixing behavior and the results were found to be useful in interpreting the flows in commercial riser exits. **Li et al. [15]** investigated numerically the gas/solid flow characteristics in a circulating fluidized bed with two different inlet configurations based on an Eulerian approach. In order to describe the interaction between the gas phase and the solid phase and the effect of the solid phase on the gas turbulence, a source term formulation was introduced. The results showed that the using of the side feeding system made the distributions of solid flow and concentration highly variable both over the column cross-section and along the column height. **Sivalingam** and **Kannadasan [16]** performed an experimental investigation on the hydrodynamic behavior of a co-current three phase fluidized bed with liquid as a continuous phase in a 54 mm id Perspex (Acrylic column) with particle size of 4.38 and 1.854 mm glass beads. Based on their experimental work, the effect of fluid rates on the various parameters such as pressure drop, porosity, gas and liquid holdups were studied and the observed data was reported. **Stojiljkovic et al. [17]** described a mathematical model of un steady one-dimensional gas to particles heat transfer for non-isothermal fluidized bed with periodic heating of solid particles. The method of numerical solution of governing differential equations, the algorithm and the computer program, had been presented. By using the mathematical model and computer program, the temperature profiles for interstitial gas, gas in bubbles, and solid particles along the height of fluidized bed in function of time had been determined. The results obtained on the basis of prediction method were compared to the experimental results and a good agreement had been found. **Abid et al. [18]** investigated the heat transfer properties in an air-fluidized bed of sand, heated with an immersed heat transfer tube positioned at several angles of inclination. Operating occurred with fluidizing velocity up to 0.5 m/s; and particles of 150–350 μm diameter. The effect of air velocity and particle size on the average and maximum achieved heat transfer coefficient was examined for the heat transfer tube at angles of inclination in the range 0-90^o. Experimental results showed that the angle of inclination altered the bubble size and behavior close to the heat transfer tube hence the expected heat transfer coefficient, with the influence of tube inclination being less pronounced for smaller particles. **Behjat et al. [19]** developed a three dimensional CFD model of the riser section of a CFB have been developed considering three phase flow hydrodynamic, heat transfer and evaporation of the feed droplets. Several experiments were performed in order to obtain the data needed to evaluate the model using a pilot scale CFB unit. The Eulerian approach was used to model both gas and catalyst particle phases comprising of continuity, momentum, heat transfer and species equations as well as an equation for solid phase granular temperature. The simulation results showed droplet vaporization caused reduction of catalyst particle residence time. However, the behavior of gas-solid fluidized systems is still not fully understood, despite their importance on the overall heat transfer enhancement. Detailed experimental and numerical techniques are required to study the flow structures of gas-solid fluidized systems in detail. From the other side , naphthalene , silica gel and sand are the most common solid particles which are used in a wide range of applications. For example, naphthalene is mainly used as a precursor to other chemicals. The single largest use of naphthalene is the industrial production of phthalic anhydride. A literature review indicates that no studies have been done on gas-solid fluidization using different solid particles such as naphthalene , silica gel and sand to study the effect of these materials on the heat transfer performance of the fluidized bed. To reach this goal, the objective of the present work is to examine experimentally the influence of using naphthalene , silica gel and sand on the heat transfer enhancement of the gas-solid fluidization process.

2- EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic diagram of the experimental apparatus for the gas-solid fluidization is shown in **Figure 1**. The fluidization column with about of (100 g), constructed from pipe, having an inner diameter of (3.175 cm) and a height of (125 cm), is placed in a vertical position. Three flow velocities of air are utilized in the experiments which are (0.8 , 1.2 and 1.6 m/sec) respectively. The gas-solid particles (naphthalene , silica gel and sand) are prepared so that, all the three materials have the same solid particle size which is approximately (197 μm).The fluidization column is attached in the considered solid particles of naphthalene , silica gel and sand. The air is supplied to the system by a compressor and the orifice is used for measuring the flow air. The manometer is used for measuring the pressure drop in fluidized bed. In order to control the gas (air) entering to the fluidized bed system a governor valve is used. The experimental apparatus consists from **[20]** :-

1- Air compressor: This air compressor pumps the required air to the air container until the pressure inside the air container satisfies the operation pressure (approximately 1.5 bar).

2- Voltage regulator : This regulator which is used for the purpose of supply power controlling.

3- Heater : This heater is attached inside a pipe. The heater capacity (1000 Watt) which supported into the pipe (D= 1.25 inch). Also, the heater is connected with a voltage regulator to control the supply power and as a results the heat flux quantity can be controlled.
4- Manometer : To measure the pressure difference on both sides of orifice meter.
5- Orifice meter : To measure the air velocity entering the fluidized bed system under steady state situation.
6-Glass pipe: The length of this pipe is (125 cm) which is divided into eight regions. In each region , K-type thermocouple is attached with an interface. The interface is linked with a personal computer.
7- Air Container : This container saves the air at a volume of (2 m^3) in order to make the air achievement to the system more stable and continuous.
8- Interface: This interface is connected with a personal computer so that the measured temperatures at various eight regions are displayed directly on the computer screen.
9- Personal computer : The specification of personal computer have hard disc 40 gaga, motherboard p4,processor 2 Gaga and ram 1 Gaga.
10- K-type thermocouple: To measure the temperatures on a computed period. The thermocouple is fixed on the glass pipe at equal distance (10 cm) from the beginning of the up to the end of the glass pipe. The number of the thermocouple is (8) which are fixed on the glass pipe.

In order to compute the coefficient of heat transfer in the gas-solid (naphthalene , silica gel and sand) fluidized bed system, the experiments for each case or state are carried for five times to make the experimental procedure more accurate and to reduce the percentage error. This procedure are repeated for the naphthalene, silica gel and sand solid particles respectively. The average of these experimental readings is taken to achieve the steady state situation. When the flow velocity of air is changed, the temperatures over the entire length of pipe are recorded. Furthermore, the temperatures over the entire length of pipe are recorded when the amount of heat flux is changed. To compute the relationship between the Nusselt number (Nu) , Froude number (Fr) and Reynolds number (Re), a STATISTICA Version 6 computer code is utilized to link all these variables together and to compute the equation constants and the following experimental equation is produced [20]:-

$$Nu_p = \frac{0.0738 \mathrm{Re}_p^{\ 0.57} Fr_p^{\ 0.48}}{5.23 + 0.0042 \mathrm{Re}_p} \qquad \begin{array}{l} 61 < \mathrm{Re}_p < 168 \\ 406 < Fr_p < 1675 \end{array} \tag{1}$$

The experimental procedure to determine the local temperature through the column, consist of the following steps. At the steady state, the heat transfer coefficient between the gas and the solid particles is determined based on the following set of equations:

3-RESULTS AND DISCUSSION

Gas-solid fluidization can be defined as the process by which solid particles (either homogeneous or heterogeneous) are transformed into a fluid-like state by suspension in a fluid (gas or liquid). This work focuses on gas-solid fluidization in which the gas phase is assumed to behave as an ideal gas in thermodynamic equilibrium. Naphthalene , silica gel and sand (197 µm diameter) are utilized in the present work as a solid particles while air is used for fluidization purpose. **Fig. 3** shows the heat flux effect on the temperature distribution along the fluidization column height for various velocities of fluidized bed (0.8 , 1.2 and 1.6 m/sec) for naphthalene solid particle and when the heat fluxes are varied as 80 , 120 and 160 W respectively .It is found that the temperature distribution along the fluidization column increases with increasing the heat flux. Also, it can be observed that as the fluidized bed velocity increases, the temperature distribution along the fluidization column increases. This is due to the increase in the solid particles enthalpy with increasing the fluidized bed velocity , since the quantity of air entering to the solid particles increases. **Fig.4** , illustrates the heat flux effect on the temperature distribution along the fluidization column height for various velocities of fluidized bed (0.8 , 1.2 and 1.6 m/sec) for sand solid particles and when the heat fluxes are varied as 80 , 120 and 160 W respectively. Again , it can be found , that the temperature distribution along the fluidization column increases with increasing the heat flux and as velocities of fluidized bed increase the temperature distribution increases. This is because when velocities of fluidized bed increase , the solid particles will be mixed efficiently with each other and as a result the temperature distribution increases. From the other hand , it is interesting to note that the temperature distribution of sand solid particles are higher than the corresponding values for naphthalene solid particles. This due to the fact that the sand solid particles have more ability to transfer thermal energy between sand molecules when velocities of fluidized bed increase. **Fig.5** explains the heat flux effect on the temperature distribution along the fluidization column height for various velocities of fluidized bed (0.8 , 1.2 and 1.6 m/sec) for silica gel solid particles and when the heat fluxes are varied as 80 , 120 and 160 W respectively. Also , it can be noticed that as velocities of fluidized bed and heat flux increase the temperature distribution along the fluidization column increases. Furthermore, the temperature distribution of silica gel solid particles are greater than the corresponding values for naphthalene solid particles, but it is still lower than the temperature distribution of sand solid particles. Therefore , it can be concluded that sand solid particles are better than the naphthalene and silica gel solid particles for heat transfer enhancement.**Fig.7** demonstrates the effect of solid particles material variation on the temperature distribution along the fluidization column height for various velocities of fluidized bed (0.8 , 1.2 and 1.6 m/sec) and when the heat flux is (80 W).Also, it can be found that the temperature distribution along the fluidization column height increases as velocities of fluidized bed increase. The reason of this behavior is due to the large amount of air entering to the solid particles which causes to increase the thermal energy of the solid particles and as a result the temperature distribution along the fluidization column increases. From this figure, it can be noticed that the temperature distribution of sand solid particles are greater than the silica gel and naphthalene solid particles for the same reason explained previously. Therefore , it can be concluded that the naphthalene solid particles have more ability to absorb thermal energy than the silica gel and sand solid particles. **Figures 8** and **9** explain the effect of solid particles material variation on the temperature distribution along the fluidization column height for various velocities of fluidized bed (0.8 , 1.2 and 1.6 m/sec) and when the heat flux are (120 W) and (160 W) respectively. It is found that the temperature distribution along the fluidization column increases with the increase of heat flux and velocities of fluidized bed. Again, the temperature distributions of sand solid particles are greater than the silica gel and naphthalene solid particles. **Fig.10** explains a comparison between the Nusselt number obtained from the suggested experimental equation with corresponding values obtained from **McGraw [21]** and **Werdermann** and **Werther [22]** as a function of Reynolds number. A good agreement can be found and lower deviations are observed between the present suggested correlation and **McGraw [21]** and **Werdermann** and **Werther [22]** correlations which verify the present experimental results indirectly.

4. CONCLUSIONS

The following conclusions can be drawn from the results of the present work.

1- For naphthalene**,** silica gel and sand solid particles, it is observed as the fluidized bed velocity and heat flux increase the temperature distribution along the fluidization column increases.

2- The temperature distribution of sand solid particles are greater than the corresponding values for silica gel and naphthalene solid particles.

3- The sand solid particles are better than the naphthalene and silica gel solid particles and it is recommended for heat transfer enhancement.

4- The naphthalene solid particles have more ability to absorb thermal energy than the silica gel and sand solid particles.

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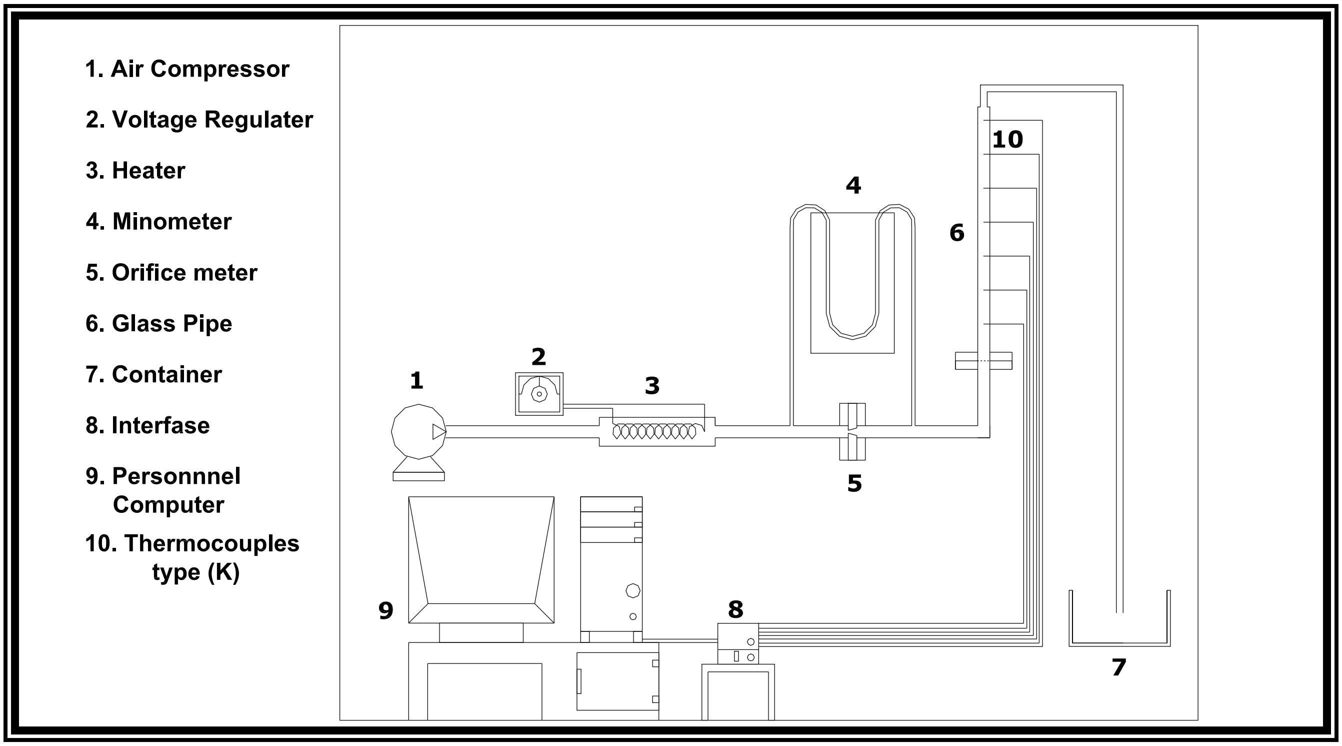

Figure (1) :The experimental apparatus [20]

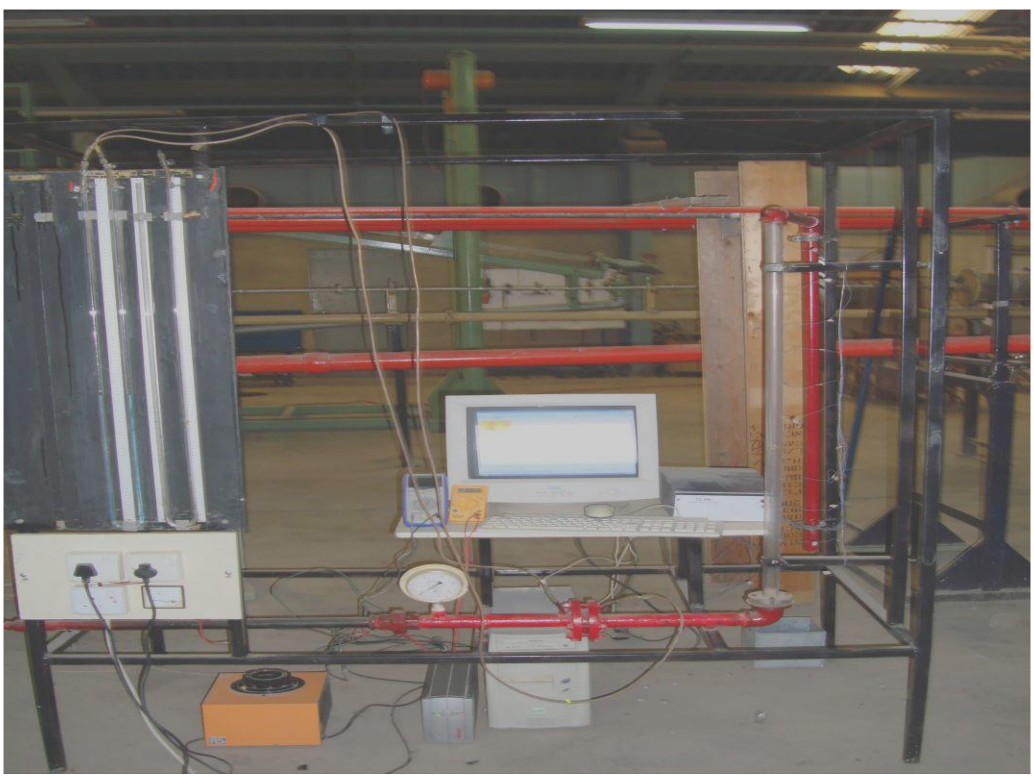

Figure (2) (A): The experimental apparatus and measurements

Figure (2) (B): The experimental apparatus and measurements

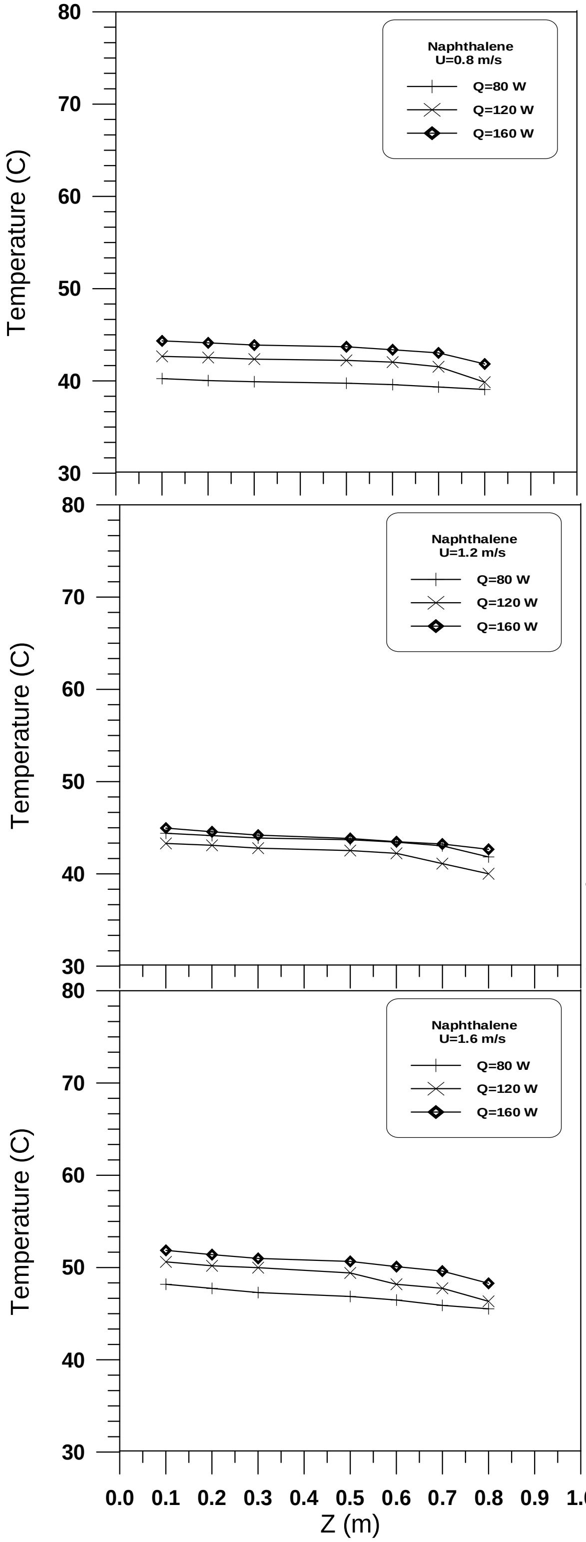

Figure (3): Effect of heat flux on temperature profile for various fluidized bed velocities for naphthalene.

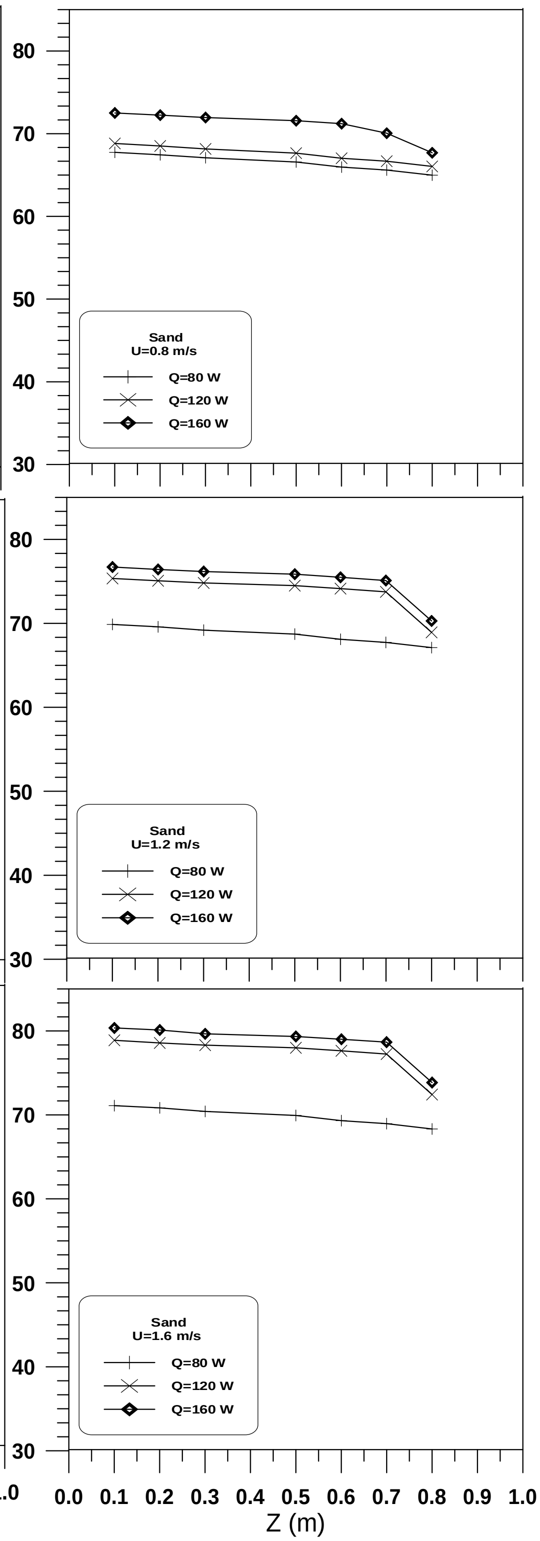

Figure (4): Effect of heat flux on temperature profile for various fluidized bed velocities for sand.

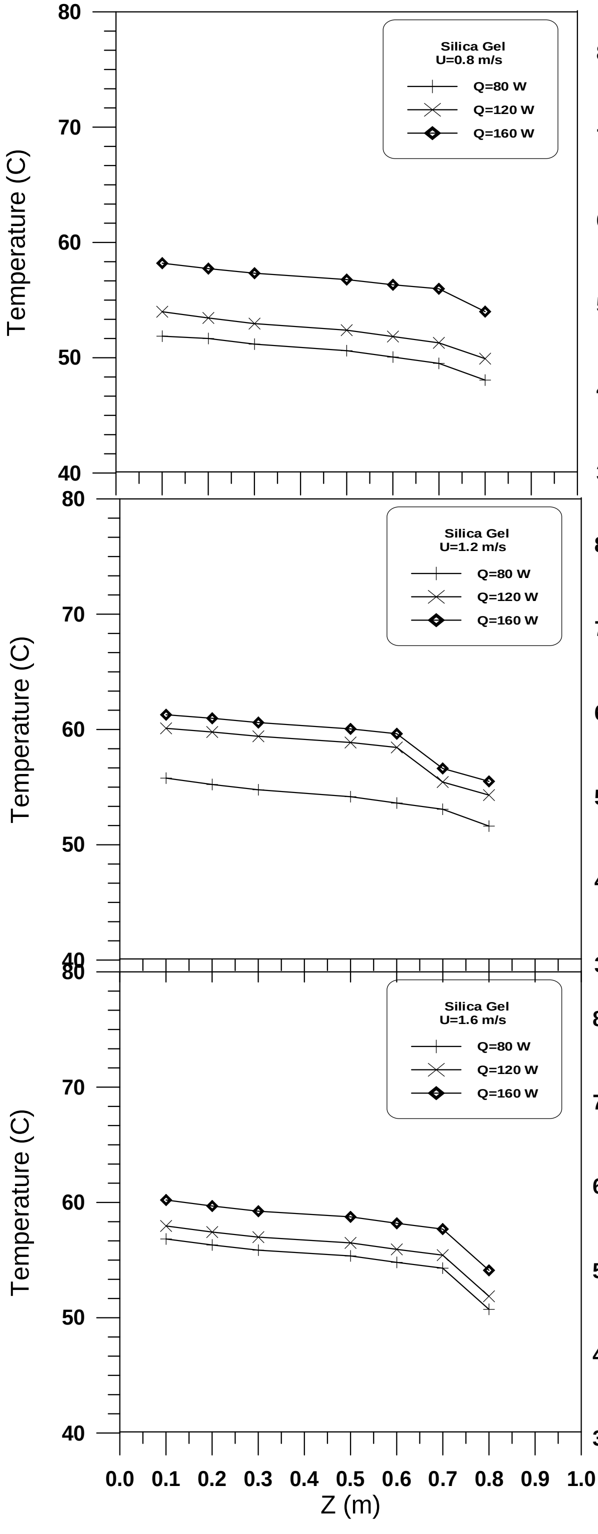

Figure (5): Effect of heat flux on temperature profile for various fluidized velocities for silica gel

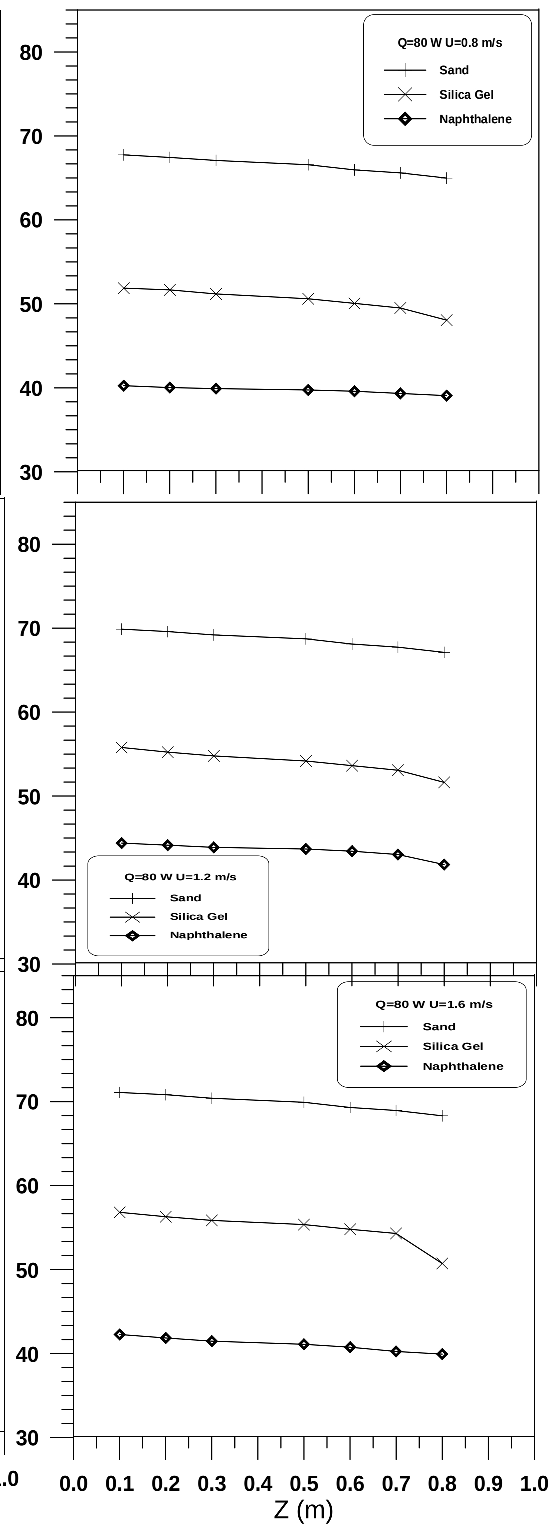

Figure (6): Effect of solid particles material variation on temperature profile for various fluidized velocities at heat flux (80 Watt)

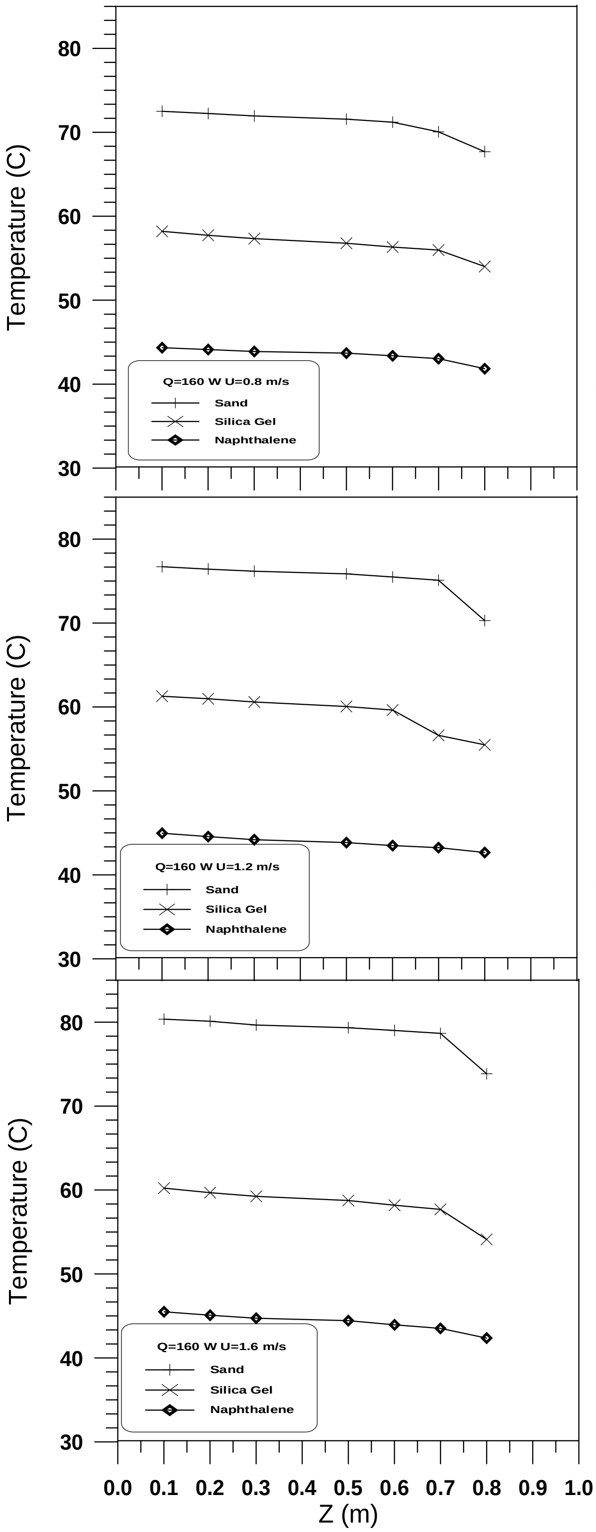

Figure (8): Effect of solid particles material variation on temperature profile for various fluidized velocities at heat flux (160 Watt)

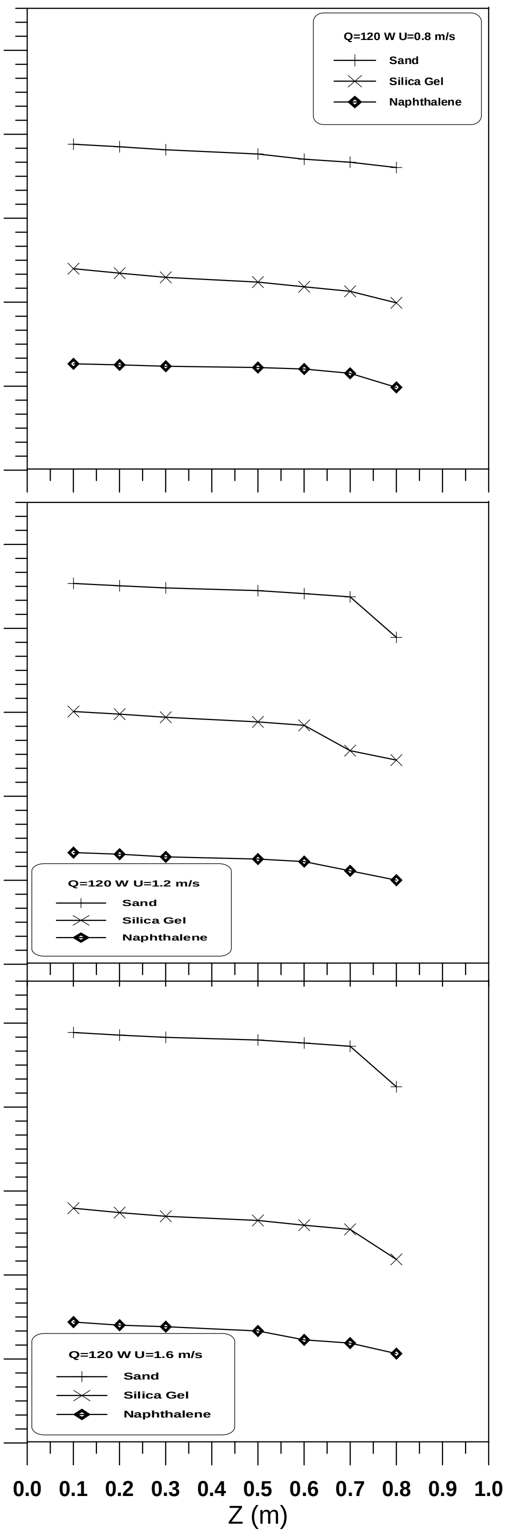

Figure (9): Effect of solid particles material variation on temperature profile for various fluidized velocities at heat flux (120 Watt)

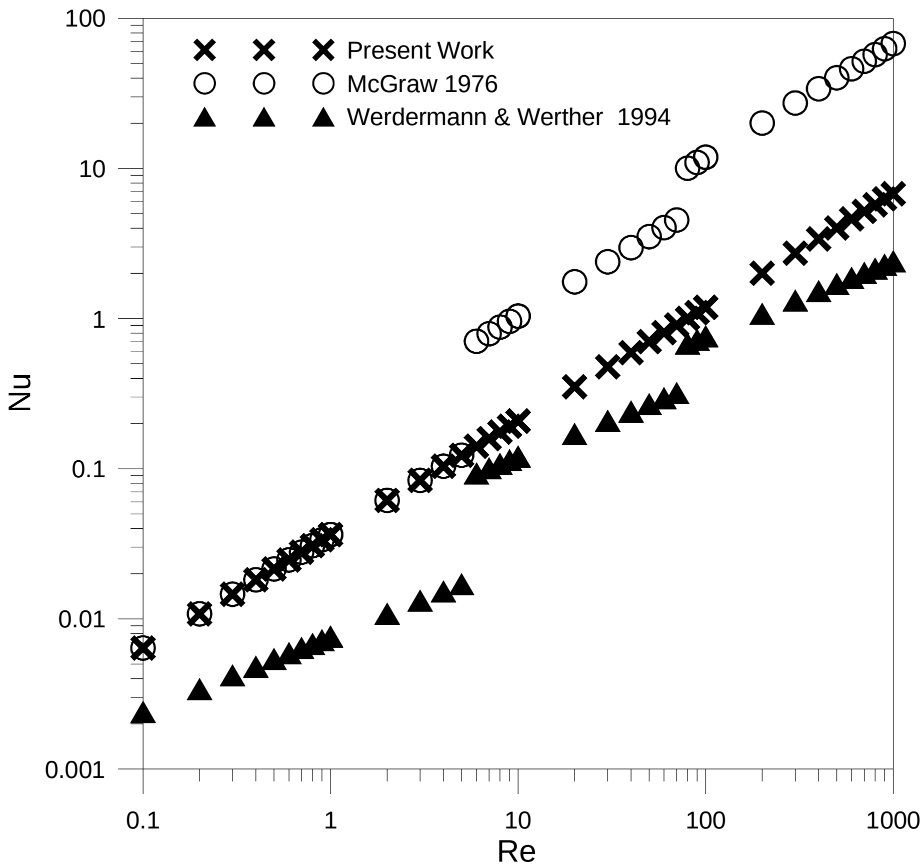

Figure (10): Effect of solid particles material variation on temperature profile for various fluidized velocities at heat flux (160 Watt)[20]